Optimal Battery Charging for Damage Mitigation

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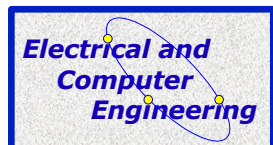**Akron, OH 44325-3904**
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Electrical and Computer Engineering

Two Phases of Control System Design:

Phase I is the design of optimal trajectories and associated inputs, that move a given plant from one operating condition to another, while minimizing some performance measure. Requires a nonlinear dynamic model of the specific system.

Phase II is the design of a trajectory following controller (sometimes called a regulator or tracker) that provides a real-time control input perturbation to keep the plant operating near the designed optimal trajectory. Usually uses a linearized dynamic model of the specific system.
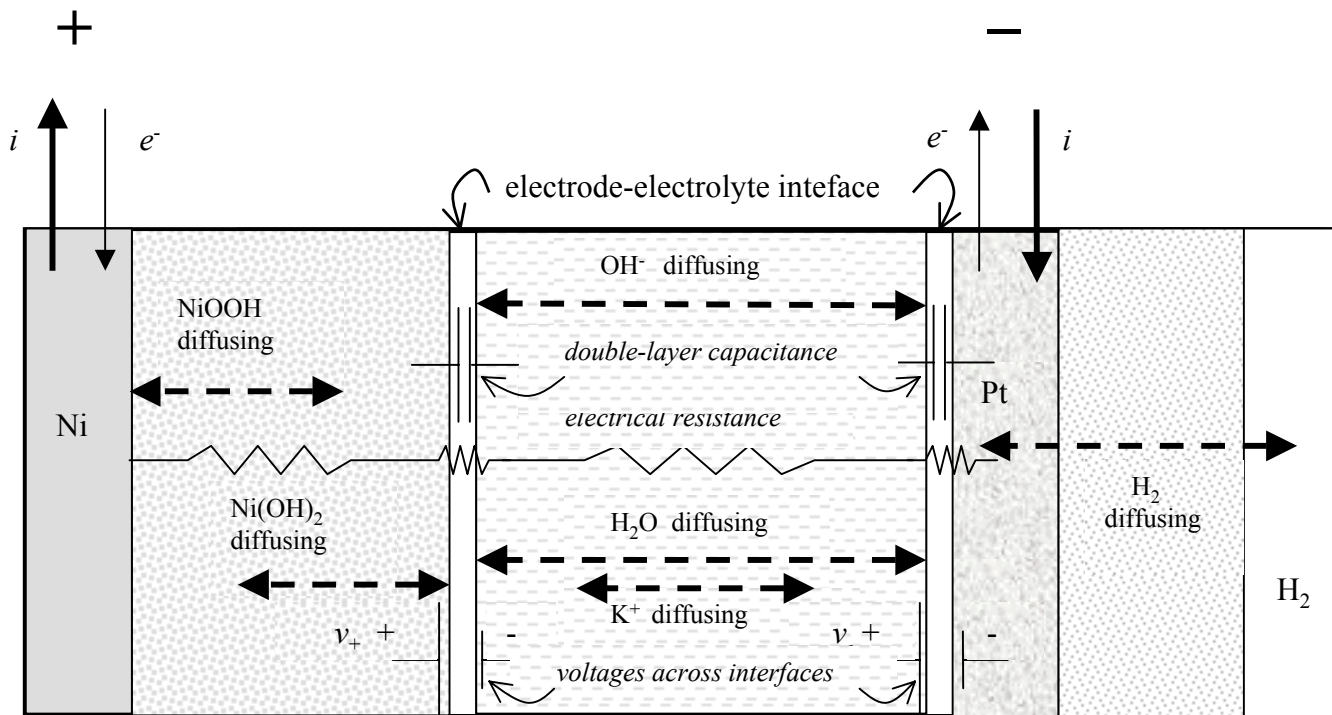
Phase I:
Our control philosophy is to charge the NiH2 cell in such a way that the damage incurred during the charging period is minimized, thus extending its cycle life. Requires nonlinear dynamic model of NiH2 cell and a damage rate model. We must do this first.
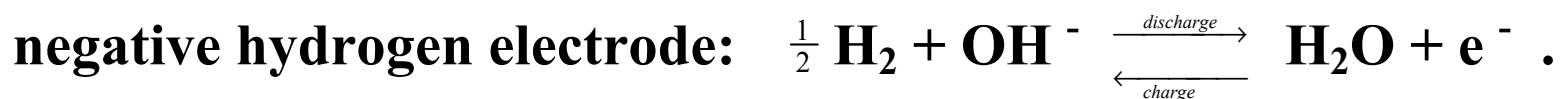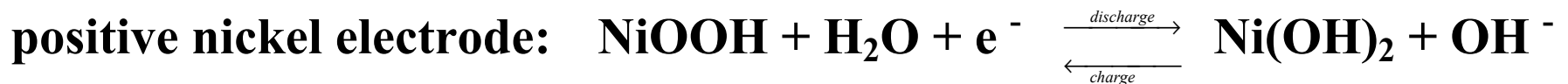This control philosophy is generally considered damage mitigating control or life-extending control.

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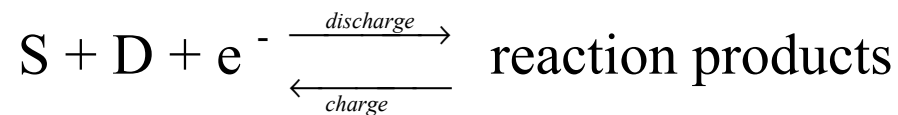
+   −

electrode-electrolyte inteface

OH^- diffusing

NiOOH diffusing

double-layer capacitance

electrical resistance

Ni

Pt

$Ni(OH)_2$ diffusing

H_2O diffusing

H_2 diffusing

K^+ diffusing

H_2

voltages across interfaces

Normal charge-discharge operation of a nickel-hydrogen cell:

positive nickel electrode: $\quad \mathbf{NiOOH + H_2O + e^-} \xrightarrow[\text{charge}]{\text{discharge}} \mathbf{Ni(OH)_2 + OH^-}$

negative hydrogen electrode: $\quad \mathbf{\frac{1}{2} H_2 + OH^-} \xrightarrow[\text{charge}]{\text{discharge}} \mathbf{H_2O + e^-}$.

storage

R_{sd} C=1 c_s $+j_s(i)$ $+i$

$+$

$-$

$+$

$v(i, c_s, c_d)$

$-$

diffusion

$k\,s^{-q}$

$+$

c_d $+j_d(i)$

$-$

$+$

c_{bulk}

$-$

chemical side **electrical side**

$$S + D + e^- \underset{\substack{\longleftarrow \\ charge}}{\overset{\substack{discharge \\ \longrightarrow}}{}} \text{reaction products}$$
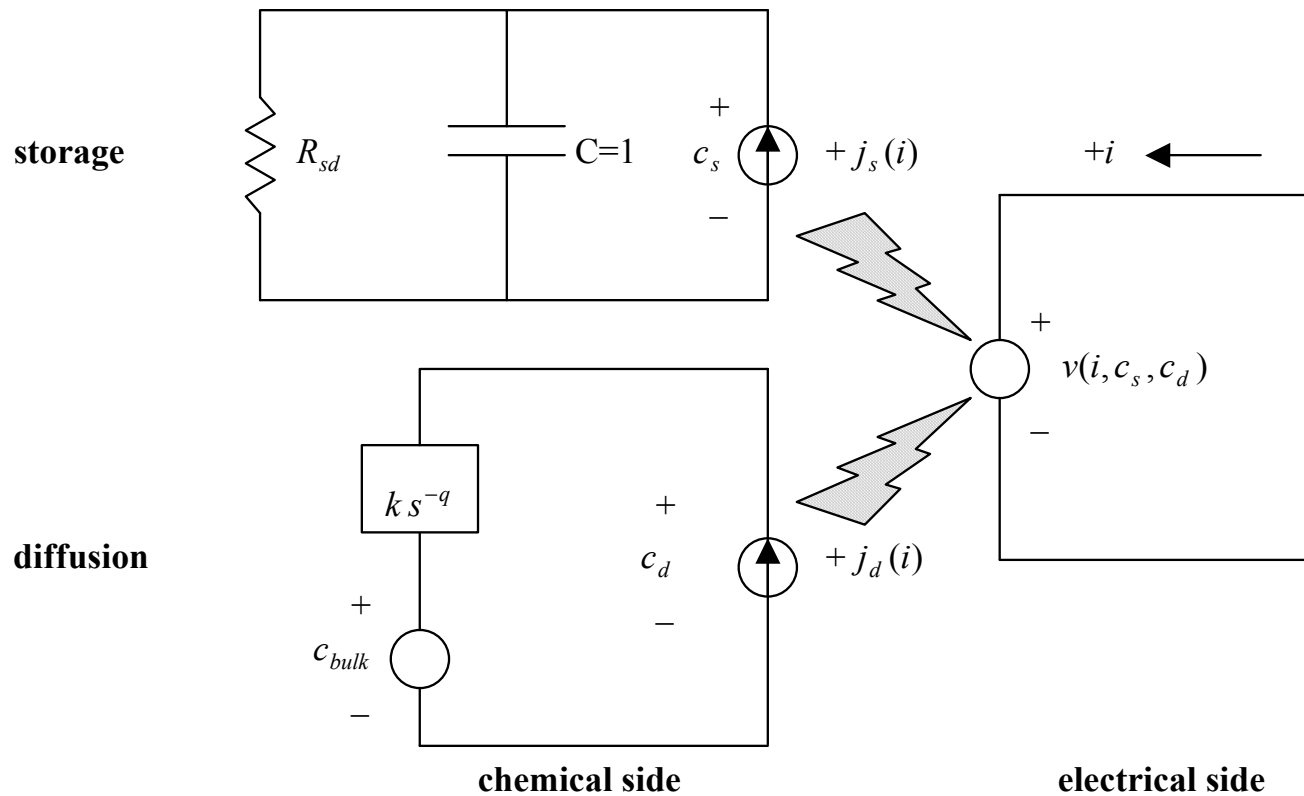
- For the discussion of the next two sections, consider the electrode process :

$$aA + bB \longleftrightarrow cC + dD + ne^-.$$
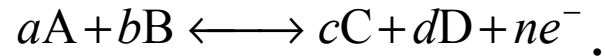
- This equation represents both a chemical process and an electrical process.

- The reaction rates can be completely determined using the electrical process by seeing that the chemical conversion can only occur if electrons are either arriving or leaving.

- Thus, the chemical conversion rates are controlled by, or measured by, the electrical current passing through a given electrode.

- Then recognizing that the rate of electron production is related to electrical current *i*, the following rate equations result :

$$-i \equiv \frac{dq_{e^-}}{dt} = -\frac{d}{n}\frac{dD}{dt} = -\frac{c}{n}\frac{dC}{dt} = +\frac{a}{n}\frac{dA}{dt} = +\frac{b}{n}\frac{dB}{dt}$$

where q_{e^-} is the charge of a single electron.

Consider the fluxes, *j*, of the species in the forward and reverse reactions at the electrode,

$$i = j_f - j_r.$$

Assuming that the species fluxes are proportional to concentrations, yields

$$i = k_f c_A^a c_B^b - k_r c_C^c c_D^d.$$

The rate constants, **k**, can be related to the electrical potential across the electrode-electrolyte interface using free energy considerations,

$$k_f = k_0 e^{(F/RT)(1-\alpha)(v-v_0)}$$

$$k_r = k_0 e^{(F/RT)(-\alpha)(v-v_0)}$$

Inserting these gives the electrode equation,

$$i = k_0 \left(c_A^a c_B^b \, e^{(F/RT)(1-\alpha)(v-v_0)} - c_C^c c_D^d \, e^{(F/RT)(-\alpha)(v-v_0)} \right).$$

The approach used is often referred to as the **Butler-Volmer approach**.

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We propose a linear-in-the-parameters approximate solution to the electrode equation;

$$v = k_1 + k_2 \ln(1 + |i|)\mathrm{sgn}(i) + k_3 \ln(c_d) + k_4 \ln(1 - c_s)$$

where the **k**'s are parameters to be determined from data.

This represents a compromise between the Tafel and the Nernst solutions of the electrode equation:

The Nernst solution assumes that the current is so small as to be negligible

$$v = v_0 + \frac{RT}{nF} \ln\left(\frac{c_s}{c_d}\right).$$

The Tafel solution assumes that the current is large in one direction or the other, which means that one of the two exponential terms is negligible

$$v = v_0 + \frac{RT}{\alpha nF} \ln(k_0) - \frac{RT}{\alpha nF} \ln(i).$$

Terminal behavior: **current into the battery is $+i$,**
the terminal voltage is $+v$,

stored material with self-discharge:

$$\frac{dc_s(t)}{dt} = i(t) - \frac{1}{R_{sd}}c_s(t) \,,$$

diffusing material:

$$c_d(t) = c_{bulk} - k_{d\ 0}d_t^{-q}i(t) \,,$$

electrode-equation:

$$v(c_s, c_d, i) = k_1 + k_2 \ln(1 + |i|)\mathrm{sgn}(i) + k_3 \ln(c_d) + k_4 \ln(1 - c_s) \,.$$

Parameter Determination

The cell chosen is the NSWC Crane Pack ID 3602G (Gates):

  rated at 65 AHr

  uses 31% KOH concentration

  maintained at 10 degrees C

  charge-discharge profile is a square wave

    with 35% depth-of-discharge (DOD)

    104% recharge ratio

    current is 26.29 A for 54 minutes charging

    –37.92 A for 36 minutes during discharge

  note that 65 AHr = 3900 AMin, 35% of 65 AHr = 1365.1
  AMin .

Terminal behavior: **current into the battery is +i,** the terminal voltage is +v,

stored material with self-discharge:
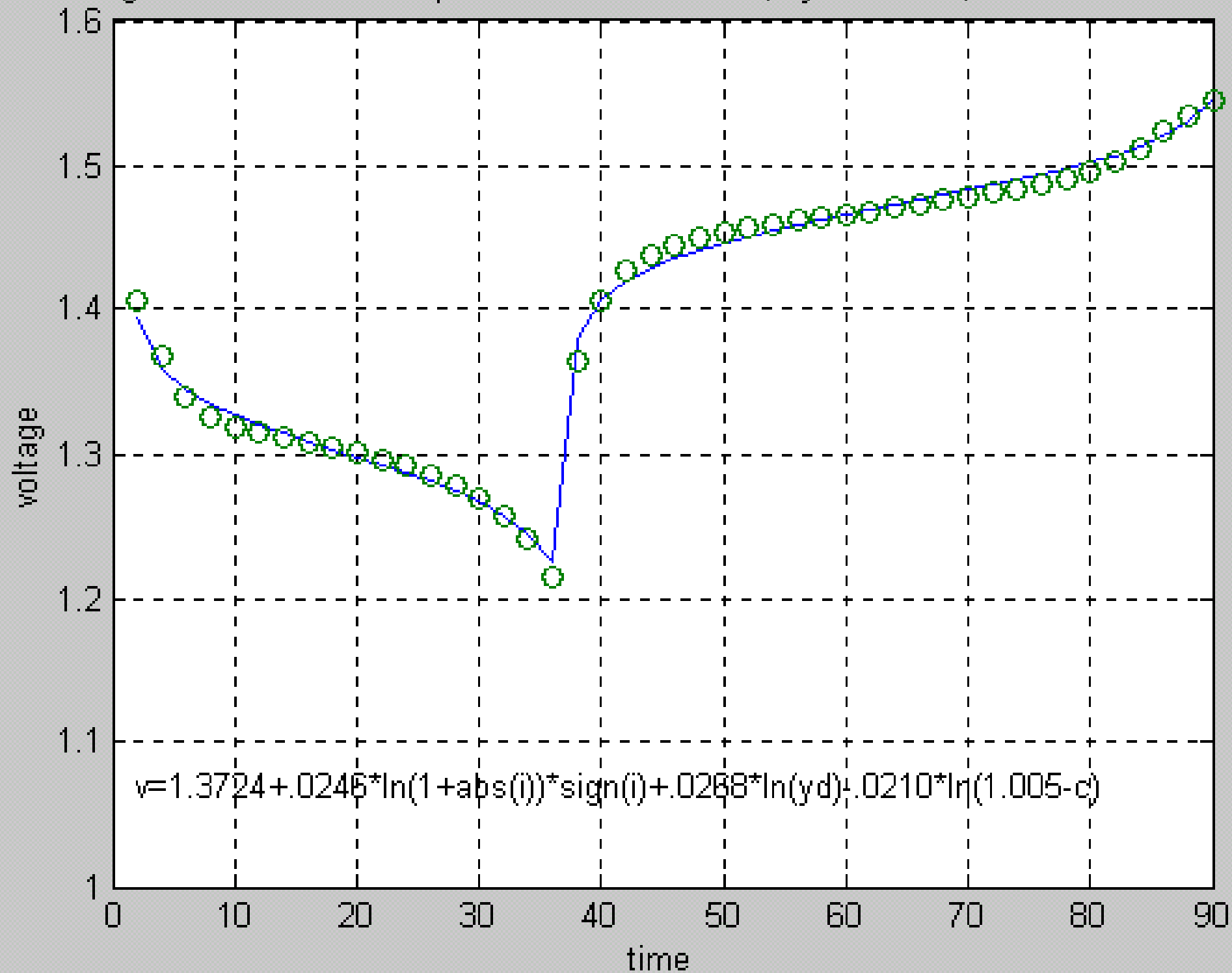
$$\frac{dc_s(t)}{dt} = i(t) - 0.0002085\,c_s(t)\,,$$

diffusing material:

$$c_d(t) = 1 - 0.001036_0\,d_t^{-0.9034}i(t)\,,$$
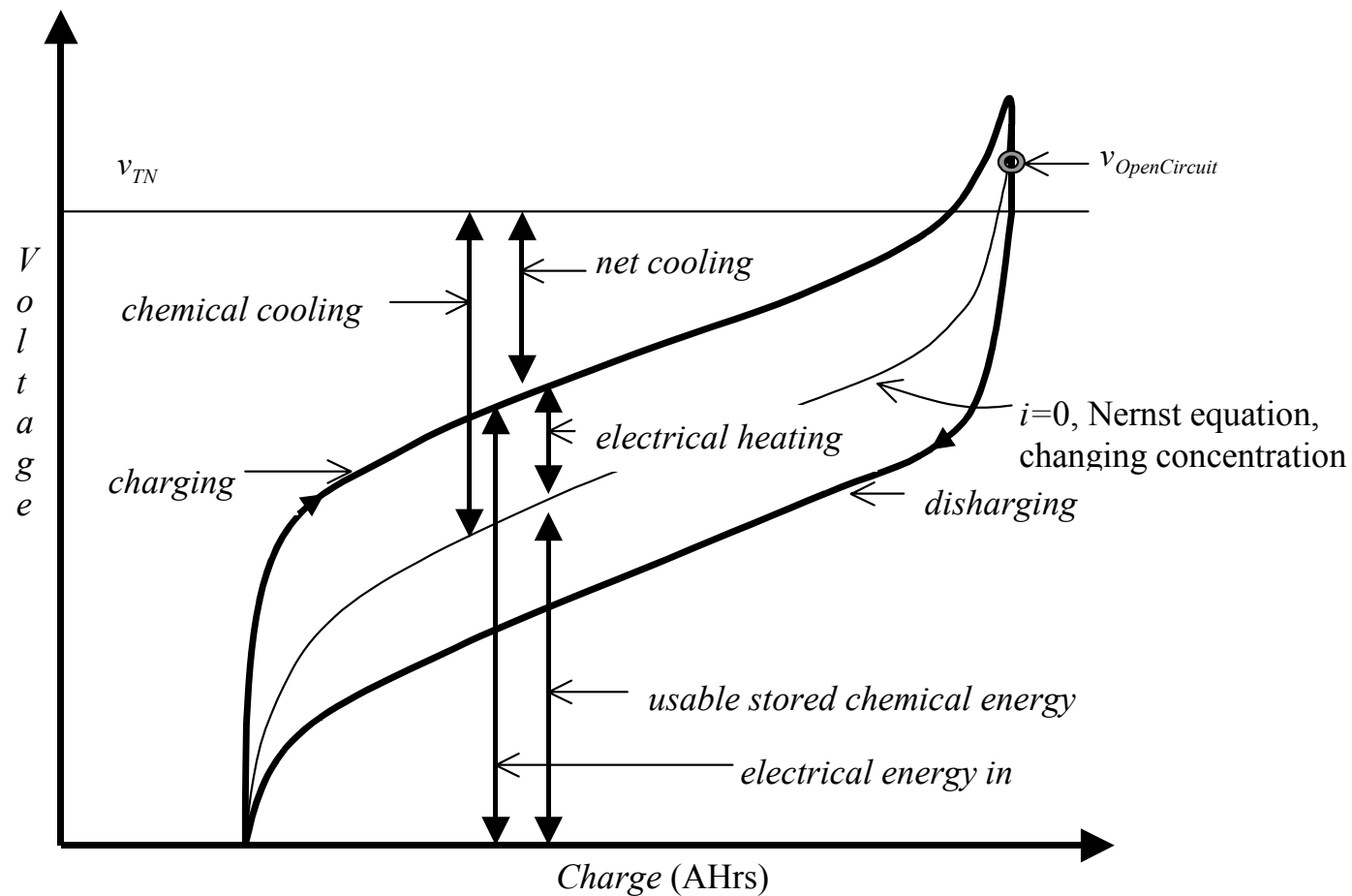
electrode-equation:

$$v = 1.3656 + 0.0265\ln\!\left(1 + |i|\right)\mathrm{sgn}(i) + 0.0229\ln(c_d)$$

$$-0.0262\ln\!\left((1.005 * 3900 - c_s)/3900\right)$$

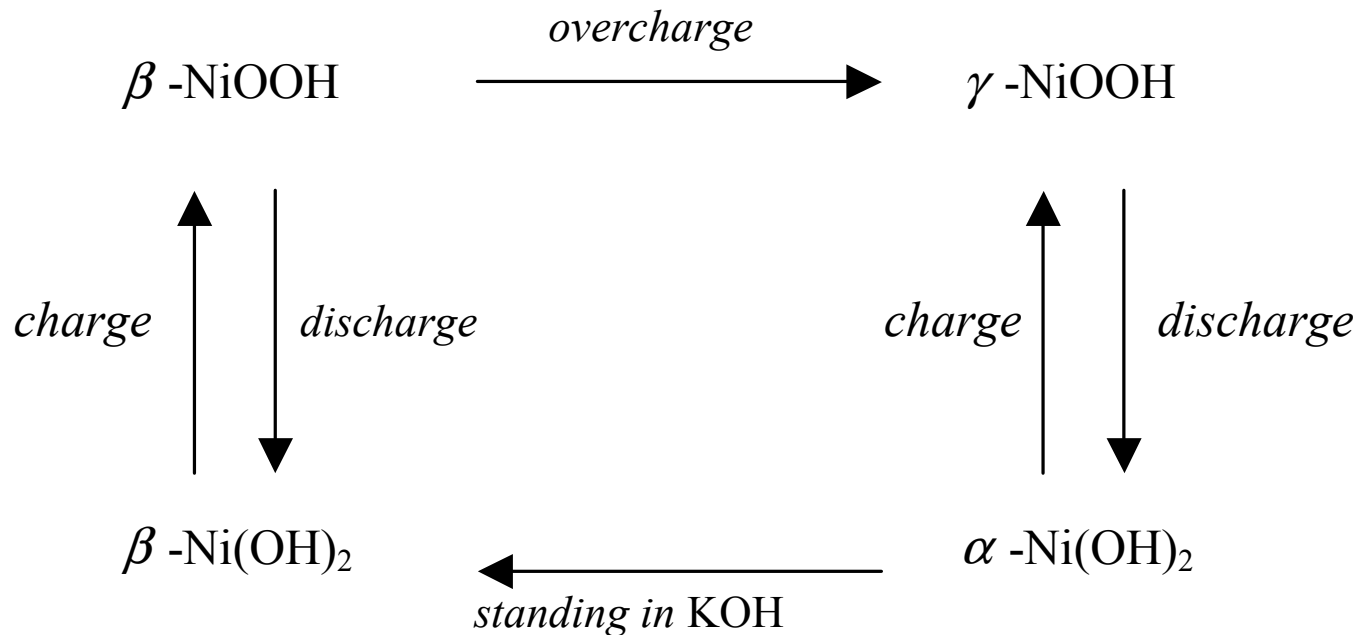voltage vs time for least squares identified model, cycle 10000, from akronbatt ls.m

$v=1.3724+.0246*\ln(1+abs(i))*sign(i)+.0268*\ln(yd)-.0210*\ln(1.005-c)$

A typical charge-discharge cycle, charging.

Formation of γ - phase NiOOH:

$$\beta\text{-NiOOH} \xrightarrow{\text{overcharge}} \gamma\text{-NiOOH}$$

β-NiOOH ⟷ γ-NiOOH

charge ↑ ↓ discharge   charge ↑ ↓ discharge

β-Ni(OH)$_2$ ⟵ α-Ni(OH)$_2$

standing in KOH

Bode's Solid phase relationships for a NiOOH electrode.

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Formation of O2:

Overcharge: 1) continuing to charge the cell after all the β-Ni(OH)$_2$ has been converted
2) the charging current is too large

The effect of this is the formation of O$_2$ at the nickel electrode, along with heating.

Damage Mechanisms for NiH2 Batteries

Heating:

Sources: 1) heat of reaction
2) formation of O_2
3) electrical current

Results in: 1) the formation of γ -NiOOH:
which a) reduces cell capacity
b) does physical damage to the cell

Results in an increase in self-discharge reaction rates.

Battery Continuum Damage Modeling

- **Many Possible Damage Mechanisms**
  - **Hard to model all these**

- **Overall Birth to Death Data will be Used Instead**

- **Crane Database Provides much Information**

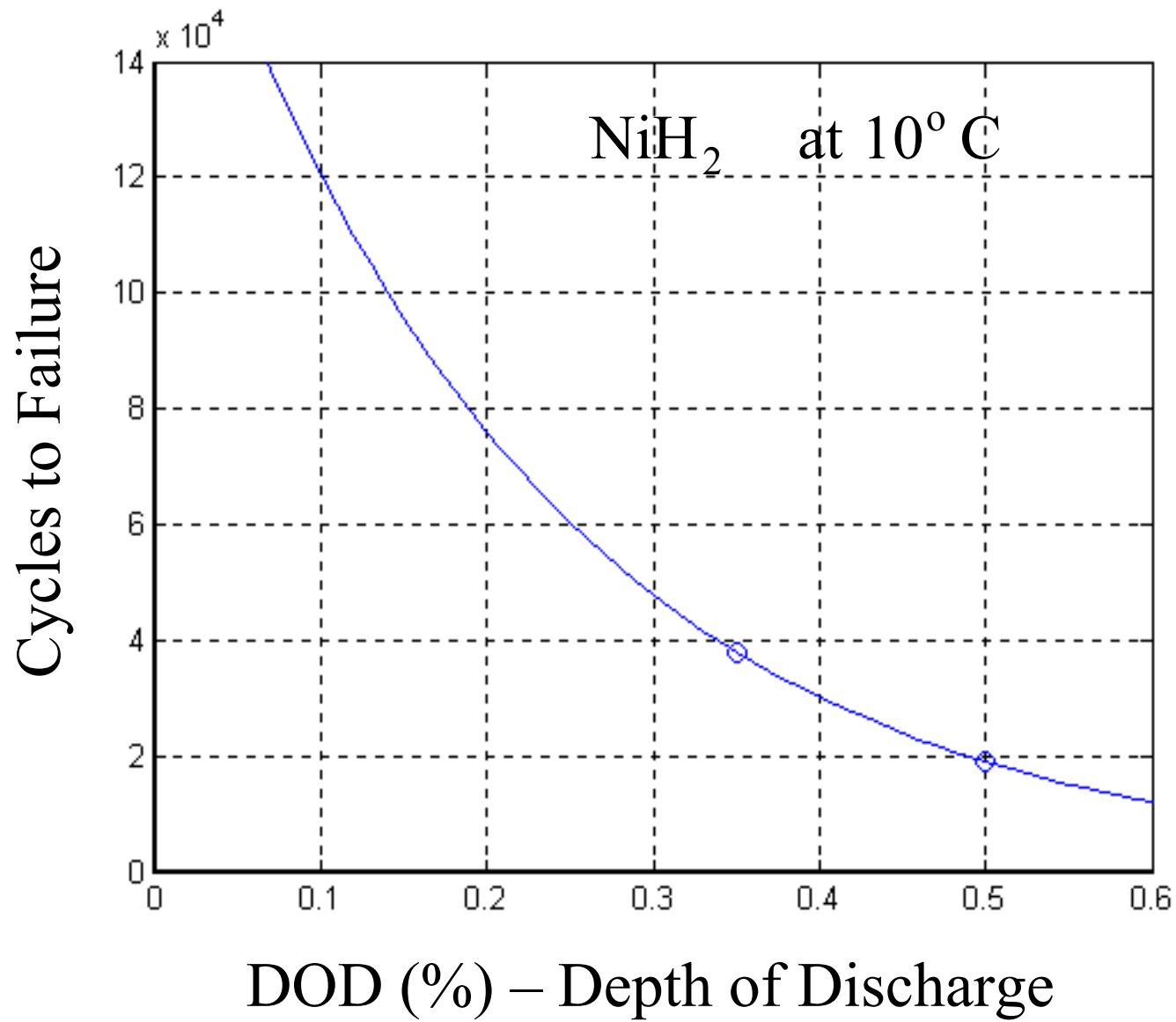- **Green-Hoffman Data Taken as Starting Point**

Green-Hoffman Data NiH_2 at $T = 10\ ^oC$

DOD	Cycles To Failure
35%	38,000
50%	19,000

Green-Hoffman Battery Life Model

NiH_2 at 10° C

Cycles to Failure

DOD (%) – Depth of Discharge

Continuum Damage Model

Based on G-H Data

$$N_{f_{GH}} = 1885.04\,e^{4.621(1-DOD)}$$

$$= 191511.73\,e^{-4.621\,DOD}, \quad \text{at } 10^{\circ}\,C$$

For constant damage per cycle

$$D_{cyc} = \frac{1}{N_{f_{GH}}} = 5.222 \times 10^{-6}\,e^{4.621\,DOD}$$

$$DOD = c_1 v_a$$

$$D_{cyc} = 5.222 \times 10^{-6}\,e^{4.621 c_1 v_a}$$

Continuum Damage Model

$$\int_{cycle} \hat{\delta}(v)\,dv = D_{cyc} = 5.222 \times 10^{-6}\, e^{4.621 c_1 v_a}$$

where $\qquad \hat{\delta}(v) = \dfrac{dD}{dv} =$ voltage referred damage rate

For damage on charging only

$$\int_{v_{min}}^{v_{max}} \hat{\delta}(v)\,dv = D_{cyc} = 5.222 \times 10^{-6}\, e^{4.621 c_1 v_a}$$

$$\int_{0}^{v_{max} - v_{min}} \hat{\delta}(v + v_{min}) \, dv = 5.222 \times 10^{-6} e^{4.621 c_1 v_a}$$

$$= 5.222 \times 10^{-6} e^{4.621 c_1 (v_{max} - v_{min})}$$

Thus inferring

$$\hat{\delta}(v + v_{min}) \cong 5.222 \times 10^{-6} \; 4.621 \; c_1 \, e^{4.621 c_1 v}$$

$$= 2.4131 \times 10^{-5} c_1 \, e^{4.621 c_1 v}$$

Hence

$$\boxed{\hat{\delta}(v) = 2.4131 \times 10^{-5} c_1 \, e^{4.621 c_1 (v - v_{min})}}$$

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Continuum Damage Model

Instantaneous Damage Rate

$$\dot{D}(t) \equiv \frac{dD}{dt} = \frac{dD}{dv}\frac{dv}{dt} = \hat{\delta}(v(t))\,\dot{v}(t)$$

Requiring Positive Damage

$$\dot{D}(t) \equiv \frac{dD}{dt} = \frac{dD}{dv}\left|\frac{dv}{dt}\right| = \hat{\delta}(v(t))\,\left|\dot{v}(t)\right|$$

$$\dot{D}(t) = 2.4131\times10^{-5}\,c_1\,e^{4.621\,c_1\,(v-v_{\min})}\left|\dot{v}(t)\right|$$

$$\dot{D}(t) = 2.4131\times10^{-5}\,c_1\,e^{4.621\,c_1\,(v-1.2)}\left|\dot{v}(t)\right|$$

For zero damage at zero DOD

$$D_{cyc} = c_2 \left(e^{c_3 DOD} - e^{c_3 \, 0} \right)$$

$$D_{cyc} = c_2 \left(e^{c_3 DOD} - 1 \right) = \frac{1}{N_f}$$

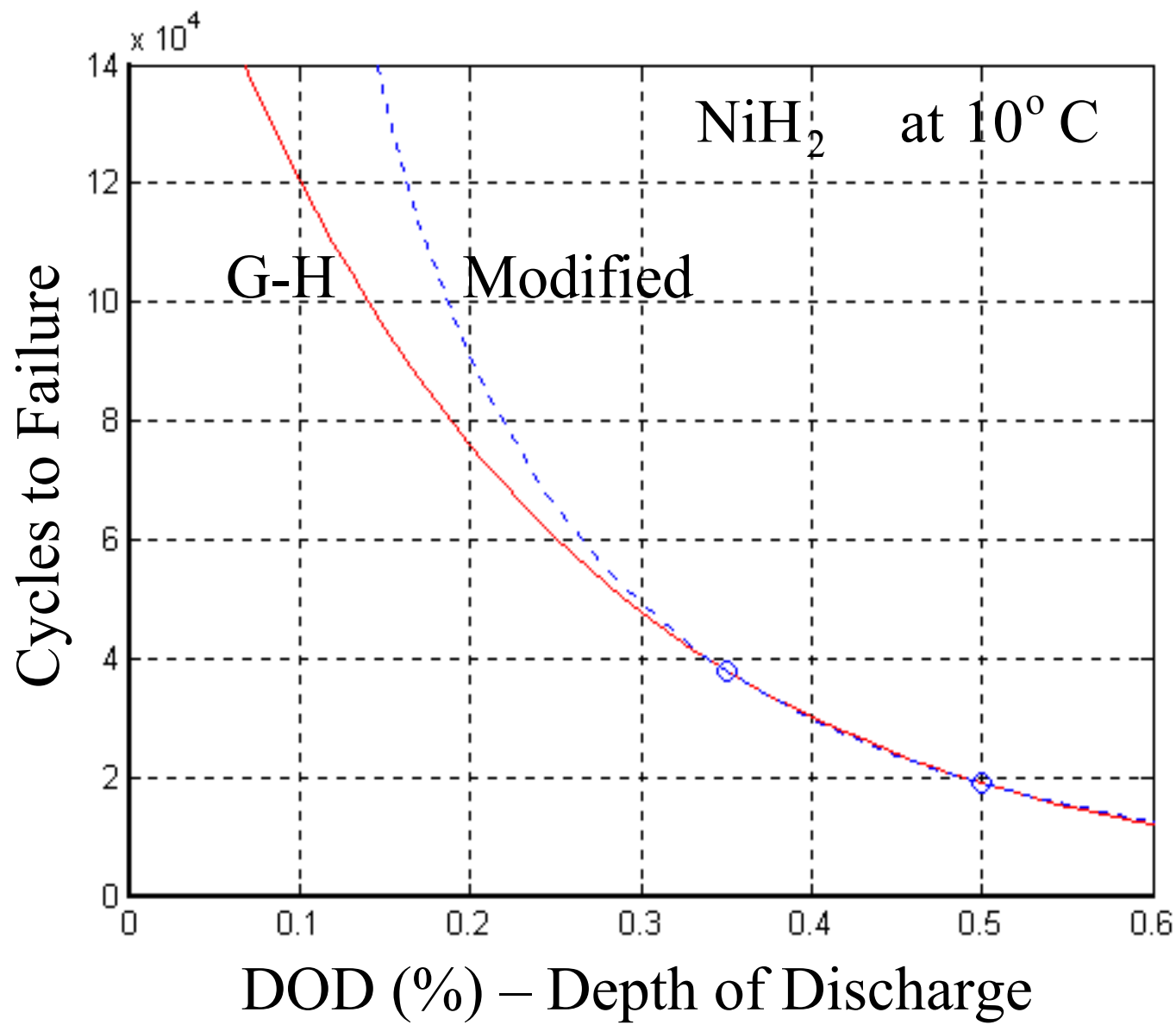c_2 and c_3 are determined to match G-H Data

$$D_{cyc} = 1.0404 \times 10^{-5} \left(e^{3.602 DOD} - 1 \right) = \frac{1}{N_f}$$

Repeating the previous process gives

$$\dot{D}(t) = 3.7475 \times 10^{-4} \, c_1 \, e^{3.602 \, c_1 (v - 1.2)} \left| \dot{v}(t) \right|$$

Battery Life Models

In terms of current

$$\dot{D}(t) \equiv \frac{dD}{dt} = \frac{dD}{dv}\left|\frac{dv}{dq}\right|\left|\frac{dq}{dt}\right| = \hat{\delta}(v(t))\left|\frac{dv}{dq}\right|\left|i(t)\right|$$

where $\dfrac{dv}{dq}$ is slope of charging curve

<u>For zero damage when voltage rate goes negative</u>

$$\dot{D}(t) = 3.7475 \times 10^{-4}\, c_1\, e^{3.602\, c_1\, (v-1.2)}\, \dot{v}(t), \quad \dot{v}(t) \geq 0$$
$$\dot{D}(t) = 0, \qquad\qquad\qquad\qquad\qquad \dot{v}(t) < 0$$

Two Phases of Control System Design:

Phase I is the design of optimal trajectories and associated inputs, that move a given plant from one operating condition to another, while minimizing some performance measure. Requires a nonlinear dynamic model of the specific system.

Phase II is the design of a trajectory following controller (sometimes called a regulator or tracker) that provides a real-time control input perturbation to keep the plant operating near the designed optimal trajectory. Usually uses a linearized dynamic model of the specific system.

Phase I:
Our control philosophy is to charge the NiH2 cell in such a way that the damage incurred during the charging period is minimized, thus extending its cycle life. **Requires nonlinear dynamic model of NiH2 cell and a damage rate model.** **Now that we have this we can begin the control design process.** The specific control philosophy is employed is generally considered <u>damage mitigating control</u> or <u>life-extending control</u>.

The **performance measure** to be minimized is the accumulated damage per recharge cycle:

$$J = w_{fs}\left(c_s^*(t_f) - c_s(t_f)\right)^2 + \int_0^{t_f} \frac{dD(t)}{dt}\,dt$$

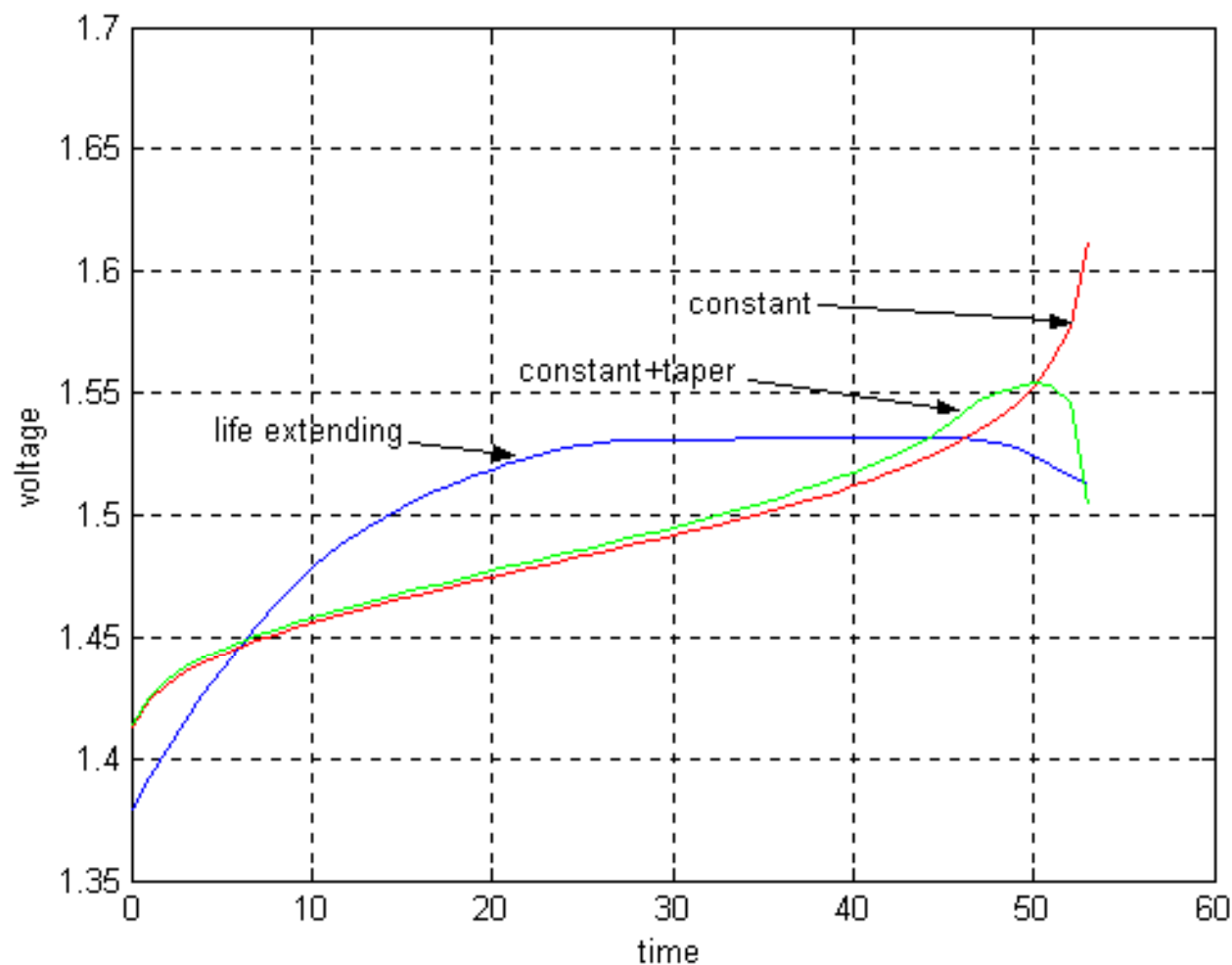$c_s^*(t_f)$ is the desired stored charge at the end of charge,

w_{fs} is the cost weighting ,

$\dfrac{dD(t)}{dt}$ is obtained from the damage model,
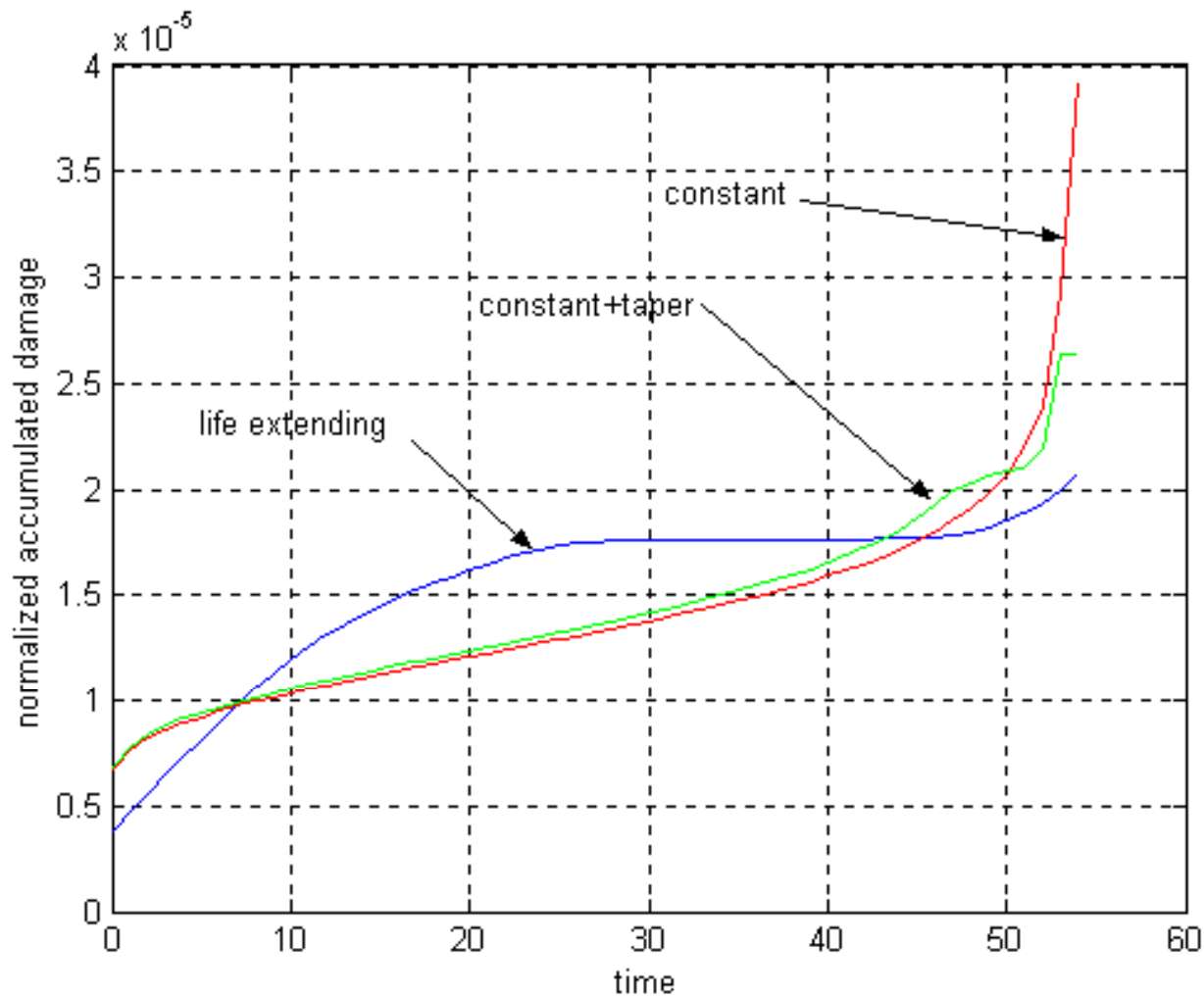
t_f for our problem is 54 Min.

Comparison of 65%-100% charging methods, voltage

Comparison of 65%-100% charging methods, damage.

Comparison of 65%-100% charging methods, current.

60%-95% recharging, voltage profile

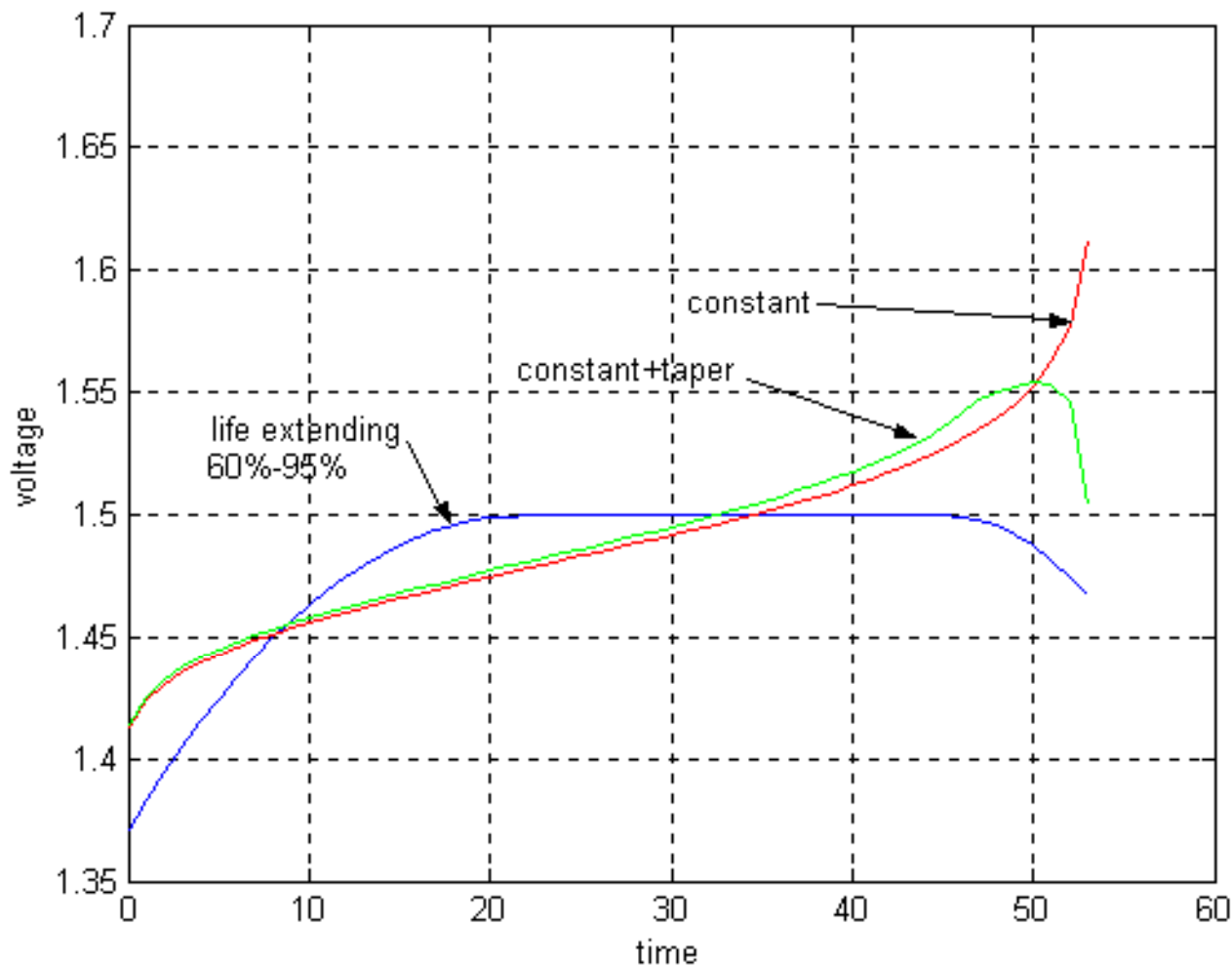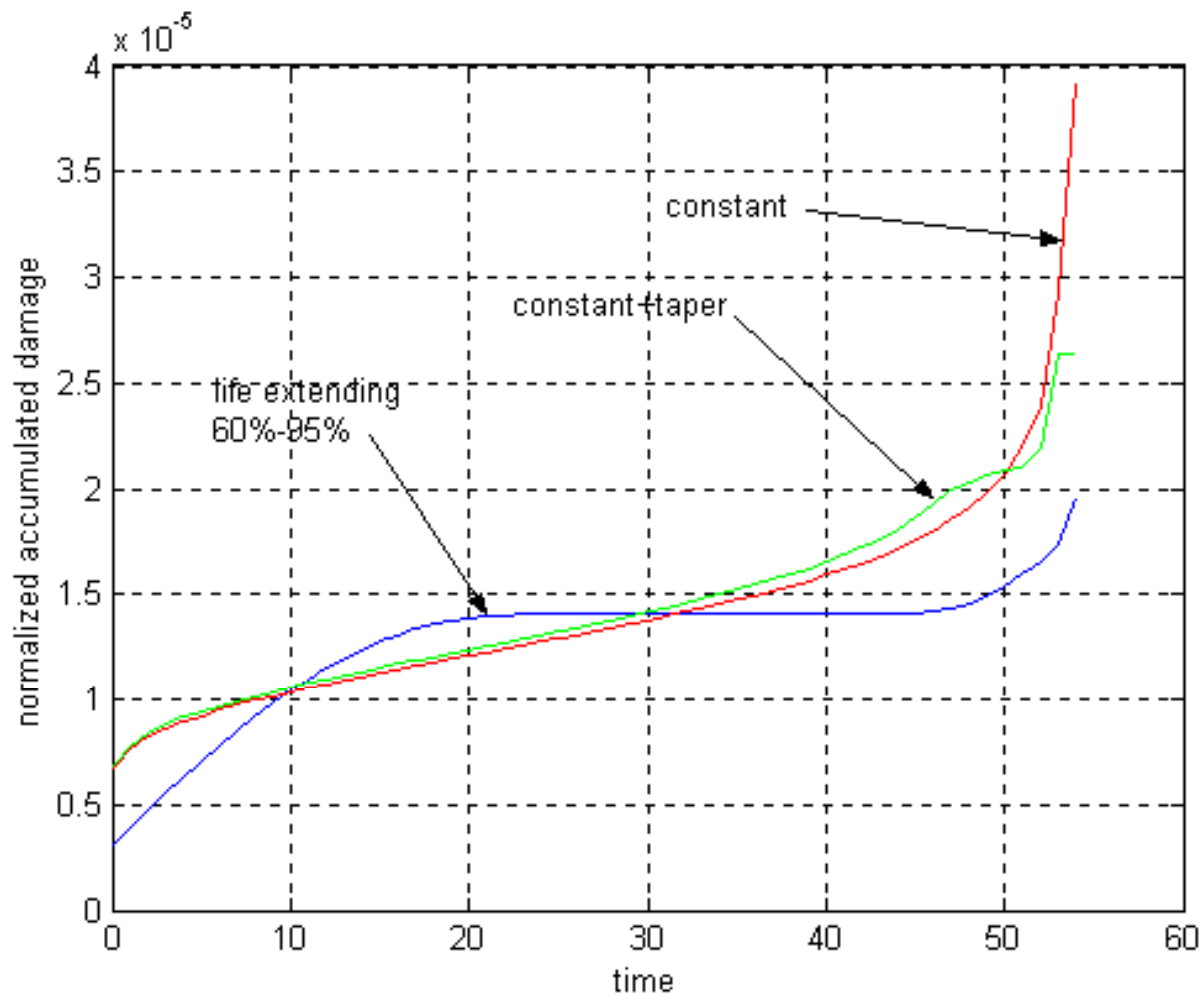Comparison of 60%-95% and standard charging methods, voltage.
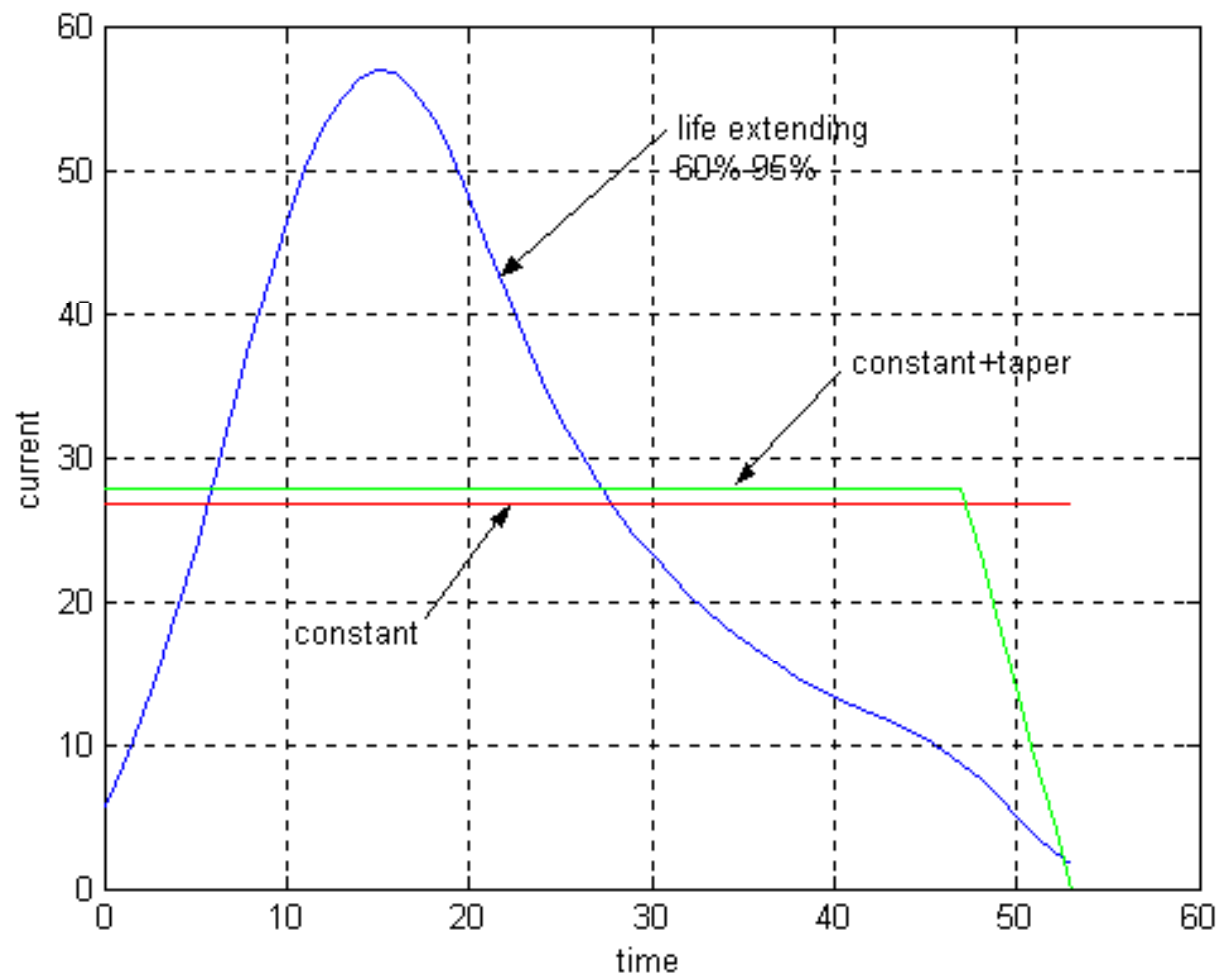
60%-95% recharging, damage profile

Comparison of 60%-95% and standard charging methods, damage.

60%-95% recharging, current profile

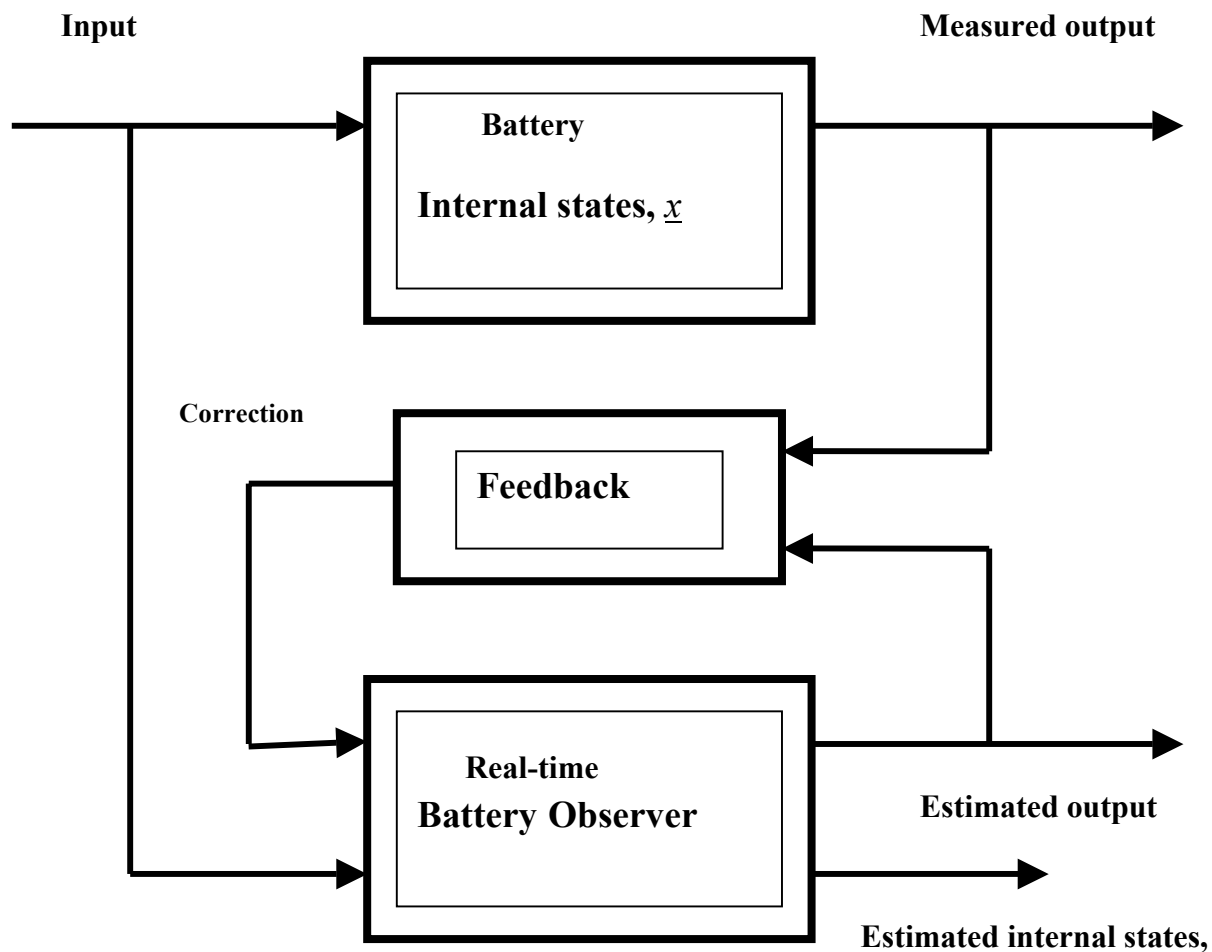Comparison of 60%-95% and standard charging methods, current.

Optimal Charging Summary

	Damage per Cycle	Cycles to Failure	% Life Extension relative to constant current	% Life Extension relative to constant current-plus-taper
Constant-Current Charging	0.000039269	25465	0%	not applicable
Constant + Taper Charging	0.000026316	38000	49.22%	0%
Life Extending Charging 65%-100% Cycle of Figure 5.4 with abs(dv/dt) damage rate	0.000020780	48123	88.98%	26.64%
Life Extending Charging 60%-95% Cycle of Figure 5.5 with abs(dv/dt) damage rate	0.000019535	51190	101.02%	34.71%
Life Extending Charging 65%-100% Cycle of Figure 5.6 with only +dv/dt damage rate	0.000022080	45290	77.85%	19.18%

Comparison of damage for various charging methods, assumes damage only during charge.
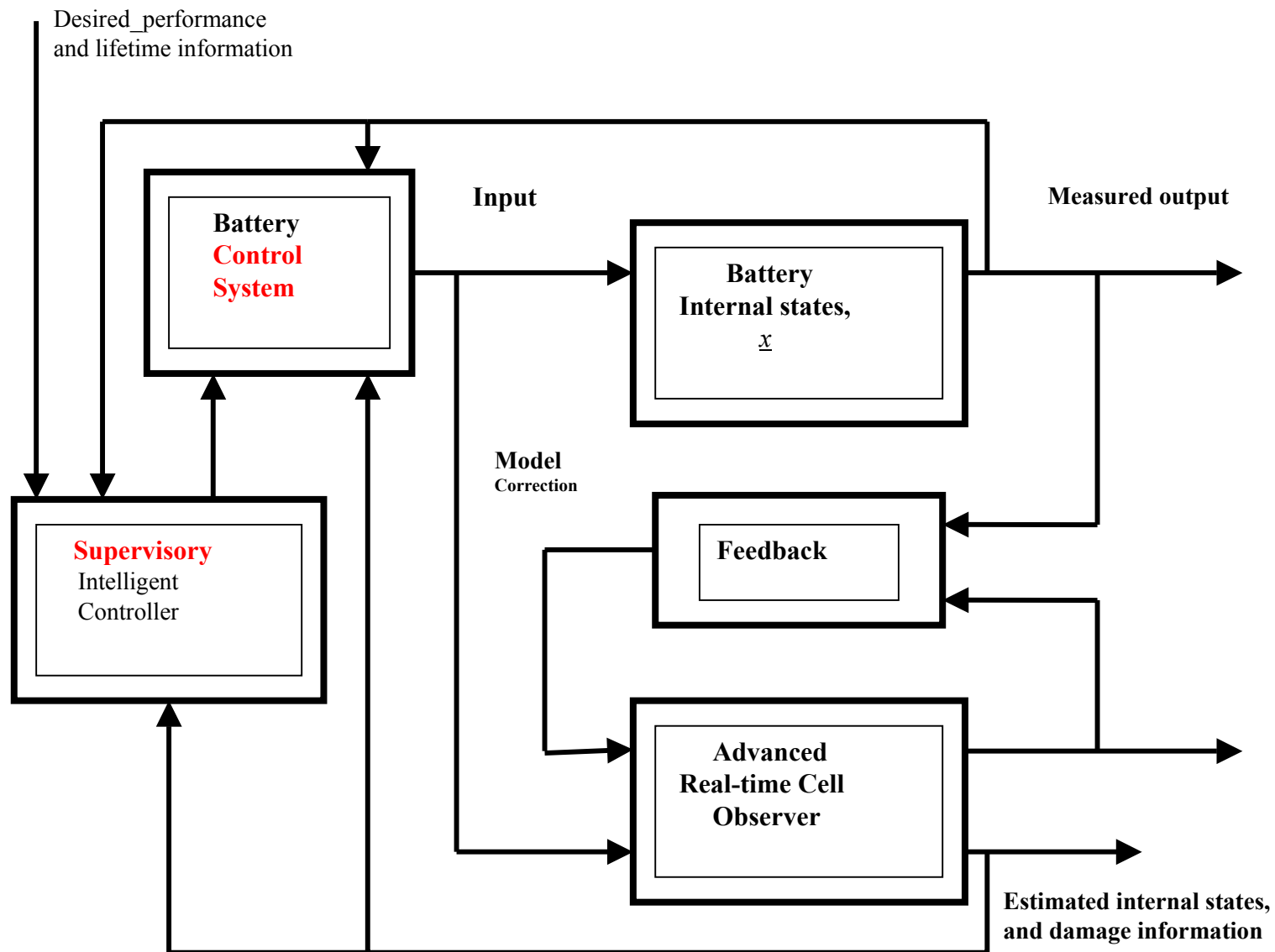Percentage life extension is reduced proportionately for damage during discharge.

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Real-time observer structure.

Desired_performance
and lifetime information

Input

Measured output

Battery
Control
System

Battery
Internal states,
x

Model
Correction

Supervisory
Intelligent
Controller

Feedback

Advanced
Real-time Cell
Observer

Estimated internal states, ,
and damage information

Advanced control system using advanced real-time observer.

Summary

- **Control Philosophy**

- **Essentialized Model Development**

- **Damage Model**

- **Optimal Life-Extending Charging**

- **Tracking Controller**

- **Real-time Parameter Identification Development**

- **Application to Lithium based cells**